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The alluvial architecture of a suspended sediment dominated meandering river: the Río Bermejo, Argentina

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ABSTRACT

The alluvial architecture of fine-grained (silt-bed) meandering rivers remains poorly understood in comparison to the extensive study given to sand-bed and gravel-bed channels. This paucity of knowledge stems, in part, from the difficulty of studying such modern rivers and deriving analogue information from which to inform facies models for ancient sediments. This paper employs a new technique, the parametric echosounder, to quantify the subsurface structure of the Río Bermejo, Argentina, which is a predominantly silt-bed river with a large suspended sediment load. These results show that the parametric echosounder can provide high-resolution (decimetre) subsurface imaging from fine-grained rivers that is equivalent to the more commonly used ground-penetrating radar that has been shown to work well in coarser-grained rivers. Analysis of the data reveals that the alluvial architecture of the Río Bermejo is characterized by large-scale inclined heterolithic stratification generated by point-bar evolution, and associated large-scale scour surfaces that result from channel migration. The small-scale and medium-scale structure of the sedimentary architecture is generated by vertical accretion deposits, bed sets associated with small bars, dunes and climbing ripples and the cut and fill from small cross-bar channels. This style of alluvial architecture is very different from other modern fine-grained rivers reported in the literature that emphasize the presence of oblique accretion. The Río Bermejo differs from these other rivers because it is much more active, with very high rates of bank erosion and channel migration. Modern examples of this type of highly active fine-grained river have been reported rarely in the literature, although ancient examples are more prevalent and show similarities with the alluvial architecture of the Río Bermejo, which thus represents a useful analogue for their identification and interpretation. Although the full spectrum of the sedimentology of fine-grained rivers has yet to be revealed, meandering rivers dominated by lateral or oblique accretion probably represent end members of such channels, with the specific style of sedimentation being controlled by grain size and sediment load characteristics.

Keywords Alluvial architecture, Argentina, fine-grained, meandering, parametric echosounder, Río Bermejo, silt-bed.

INTRODUCTION

Studies of modern coarse-grained (sand and gravel) meandering rivers, point bars and their alluvial architecture have a long history (e.g. Leopold *et al.*, 1964; Allen, 1970a,b; Bluck, 1971; Bridge & Jarvis, 1976, 1982; Smith, 1987; Bridge *et al.*, 1995) and the dynamics and deposits of these rivers have been investigated extensively. However, this situation contrasts markedly with finer-grained alluvial channels (fine sand, silt and clay), whose sedimentology is far less well-known (Jackson, 1978, 1981; Miall, 1996), although they occur in a range of modern fluvial settings including semi-arid (e.g. Page *et al.*, 2003), temperate (e.g. Brooks, 2003) and glaciofluvial (e.g. Fahnstock, 1969) environments. Such fine-grained rivers also form some very large rivers, such as the Huanghe (Yellow) River in China (Wang & Li, 2011) and have also been documented in ancient sediments (e.g. Mack *et al.*, 2003; Gruszka & Zieliński, 2008). A number of recent studies thus all conclude that the sedimentological characteristics of fine-grained rivers are not yet well-constrained and are poorly represented in current alluvial lithofacies models (Brooks, 2003; Ghosh *et al.*, 2006; Wright & Marriott, 2007).

This paucity of knowledge concerning the depositional characteristics of fine-grained meandering rivers presents considerable complexities to interpreting such deposits within the ancient sedimentary record, because it is uncertain whether models developed for coarse-grained rivers can be simply transferred to fine-grained channels. For example, fine-grained rivers tend to possess lower width/depth ratios and have a higher sinuosity when compared with coarser-grained channels (Ghosh *et al.*, 2006) and their sediment loads may generate conditions in which turbulence can be modulated (Baas & Best, 2002; Best, 2005; Baas *et al.*, 2009, 2015), resulting in bedforms with different characteristics to sand and gravel dominated channels (Baas *et al.*, 2011). All of these factors could potentially result in differences in the alluvial architecture of fine-grained rivers as compared with their gravel-bed or sand-bed counterparts. Furthermore, while the term 'fine-grained' has no strict formal definition, it probably incorporates a diverse range of channel types. These channel types may vary from those with high clay content, low sinuosity, low width/depth ratio and high stability, through to

those with low clay content but high silt load, a channel planform that can be braided, high width/depth ratios and that can be very active, such as parts of the Huanghe River. Recognizing and quantifying such differences, in order to allow a fuller appreciation of grain-size controls on sedimentary facies is of importance, because, for example, it has been suggested (Wright & Marriott, 2007) that the within-channel deposits of such fine-grained rivers may have been incorrectly interpreted to be the deposits of overbank floodplain sedimentation.

Past studies that have investigated modern fine-grained rivers have also been restricted in their methodology to analysis of cores, shallow trenches and natural cutbanks. These studies have highlighted that fine-grained rivers may contain oblique accretion (Marren *et al.*, 2006), point-bar accretion (Page *et al.*, 2003), counterpoint-bar accretion (Makaske & Weerts, 2005) or even large rotational slumps (Brooks, 2003). However, it is largely unknown whether these are the only major depositional facies, how these different components may be spatially distributed, what their relative abundance may be in the preserved sedimentary record or how different aspects of the meander morphodynamics (for example, radius of curvature, bend planform shape and migration rate) may cause variations in these depositional facies. In summary, current understanding of fine-grained meandering rivers lags that of coarser-grained channels, and their large-scale alluvial architecture remains largely unknown.

The relative lack of data from contemporary fine-grained rivers can, to some extent, be attributed to the fact that the geophysical techniques that have revolutionized the study of sand-bed and gravel-bed channels do not work in such finer sediments. For instance, the signal of ground-penetrating radar is severely attenuated in fine-grained sediment such that penetration can be zero. Thus, radar studies that have provided exceptional detail of the architecture of sand and gravel-bed rivers (e.g. Bridge *et al.*, 1995; Best *et al.*, 2003; Lunt & Bridge, 2004; Sambrook Smith *et al.*, 2006, 2009; Mumpsey *et al.*, 2007) have not been possible in fine-grained rivers. The primary aim of the present paper is to use a new technique, parametric echosounding, to provide the first large-scale, three-dimensional visualization of the alluvial architecture of a meandering fine-grained river, the Río Bermejo, Argentina. The parametric

echosounder (PES) provides data at an equivalent resolution to ground-penetrating radar, is specifically designed for use in fine-grained sediments and so provides an important first step towards quantifying the alluvial architecture of fine-grained rivers. The present paper has four principal objectives:

- 1 To use remote sensing imagery to describe the planform shape, radius of curvature, migration rates and styles of meander bend evolution within the study reach.

- 2 To describe the full range of depositional facies within the channels of the study reach based on analysis of PES survey data.

- 3 To determine the influence of the observed morphodynamics on the resultant alluvial architecture.

- 4 To compare the results from the Río Bermejo with other modern and ancient fine-grained rivers reported in the literature.

STUDY SITE

The Río Bermejo, which originates in Bolivia, is an undammed tributary of the Río Paraguay with a drainage area of 123 162 km². It has a very high suspended sediment load, with 98% of its sediment discharge transported in suspension and an overall sediment yield of 100×10^6 tons per year (Orfeo *et al.*, 2006; Iriondo & Orfeo, 2012). The study site is located in the most distal reach of the river, in Argentina, just upstream from its confluence with the Río Paraguay. The subtropical climate results in heavy summer rain (mean annual precipitation varies from 600 to 1200 mm yr⁻¹ across the basin; Cobinabe, 2010) and a predictable seasonal discharge that is greatest during January to April, and accounts for *ca* 75% of the annual flow. In the downstream reaches, peak flows typically occur in February and range from 1000 to 2000 m³ s⁻¹ (Cabo & Seoane, 2005), dropping to <50 m³ s⁻¹ in October. During these high flows, the channel width is *ca* 200 m and thalweg depth ranges between 4 m and 10 m within the study reach. In upstream reaches, near the Bolivian border, the mean grain size of bed sediments is medium sand; this decreases to a sandy silt ($D_{50} = 74 \mu\text{m}$; 60% sand, 37% silt and 3% clay) from Las Lomitas all the way downstream to the study reach, *ca* 290 km straight-line distance (Iriondo & Orfeo, 2012). The Río Bermejo is characterized by very high suspended sediment concentrations, with average concentrations of

10,000 mg L⁻¹ being common within the river (Amsler & Drago, 2009). Over the past 1000 years, the river has been aggradational, with periodic avulsions followed by reoccupation of channel belts (Iriondo, 1993). The river is still highly active today, with high reach-averaged lateral channel migration rates of 20 to 30 m yr⁻¹ (for example, 2000 to 2001 *ca* 32 m yr⁻¹; 2003 to 2005 *ca* 19 m yr⁻¹; 2005 to 2009 *ca* 25 m yr⁻¹; 2009 to 2012 *ca* 21 m yr⁻¹) as measured from sequential Landsat images. In summary, the Río Bermejo is similar to other fine-grained rivers, such as the Huanghe River, which are dominated by silt as opposed to clay, and thus the Río Bermejo possesses a relatively large width/depth ratio and high rates of channel migration. It should also be noted that rivers with these characteristics are likely to be prevalent over a considerable area. For example, Orfeo (1999), based on a study of 30 rivers in the same region as the Río Bermejo, concluded that deposition was dominated by similar alluvial sediments over the entire Eastern Chaco region in Argentina, from 20 to 30°S, and that rivers dominated by silt with high suspended loads fed by loessic headwaters were prevalent.

The planform of the Río Bermejo in the study reach at the time of the present field study consisted of three bends of differing morphology (Fig. 1B) with an average sinuosity of 1.94 (measured from the February 2012 centreline). Images dating back to 1987 indicate that the study reach is actively migrating through an alluvial floodplain characterized by scroll bar topography and the fill of several oxbow lakes (Fig. 2). The recent planform evolution of the study reach is a product of the interaction between the processes of lateral migration and bend cut-off. Between 1987 and 2001, development of a double-headed meander bend in Bend 2 contributed to a rapid increase in sinuosity (Fig. 2). As a result, a neck cut-off occurred on Bend 1 between 2001 and 2002, locally straightening the channel planform. This cut-off was followed by rapid expansion and development of lobes within the meander of Bend 1 between 2002 and 2012, thus creating a local sinuosity of 2.20 by February 2012. This pattern of planform evolution follows the cycle of neck cut-off described for the Mississippi River by Gagliano & Howard (1984). Bend 2 also underwent a period of bend expansion subsequent to the neck cut-off, followed by widening of the channel and development of a concave-bank bench (Hickin, 1979, 1986; Page & Nanson, 1982) at the bend apex. The present-day sinuosity of Bend 2 is 2.45. In contrast, Bend 3 (Fig. 2)

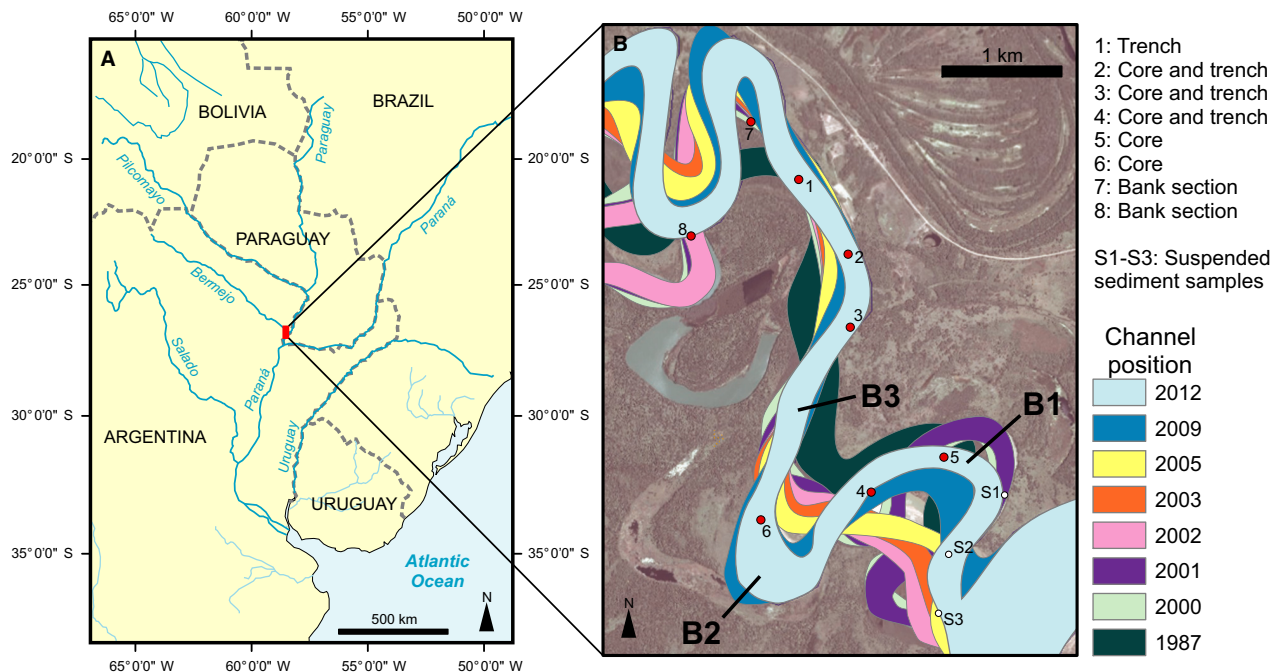


Fig. 1. (A) Location map of the Río Bermejo field site. (B) Map of the distal section of the Río Bermejo, with Bends 1, 2 and 3 indicated that are the focus of this paper. Channel positions from 1987 to 2012 are shown, together with locations of the survey sites discussed in the text.

has evolved slowly in comparison with Bends 1 and 2, producing a low-amplitude bend with a sinuosity of 1.14.

It should be noted that the deposits described below relate to those of the active point bars and channels. It is evident from the description of channel evolution given above that the channels are extremely active, and this suggests that such deposits will comprise a significant proportion of the alluvium of the Río Bermejo. However, significant areas of overbank sedimentation within quiescent environments are also present, such as in the infill of the numerous meander cut-offs (see Fig. 2). These areas of overbank deposition were not the main focus of this study, and hence the results presented herein should be viewed within the context of within-channel sedimentation.

METHODS

Geophysics

The parametric echosounder (PES) used in this study was an Innomar SES-2000 Light (Innomar Technologie GmbH, Rostock, Germany) that was deployed from a small research vessel during high flows in late February/early March 2012. A

brief outline of the PES system is provided herein, with more details given in Sambrook Smith *et al.* (2013). The key feature of a PES is that it transmits two signals of slightly different frequency (100 kHz and a selectable lower frequency between 4 kHz and 15 kHz) and, because of the non-linearities in sound propagation at high pressures, both signals interact resulting in the production of new frequencies. The high-frequency signal gives an exact determination of water depth, as is the case for any standard echosounder. However, the low frequency signal penetrates the bed surface, with reflections produced from primary sedimentary structures in the same way as much larger seismic systems. Data on the bed topography and the associated underlying sedimentary structure are thus collected *simultaneously*.

Another significant feature of the PES is that it has a high system-bandwidth that means short signals can be transmitted without ringing. The importance of this characteristic is that the PES can be used in much shallower water depths, of minimum *ca* 1.5 m, than would typically be the case for standard seismic systems, thus making it ideally suited for use in rivers. Finally, the PES has a small beam width and high-frequency bandwidth that yield bottom echoes with a stee-

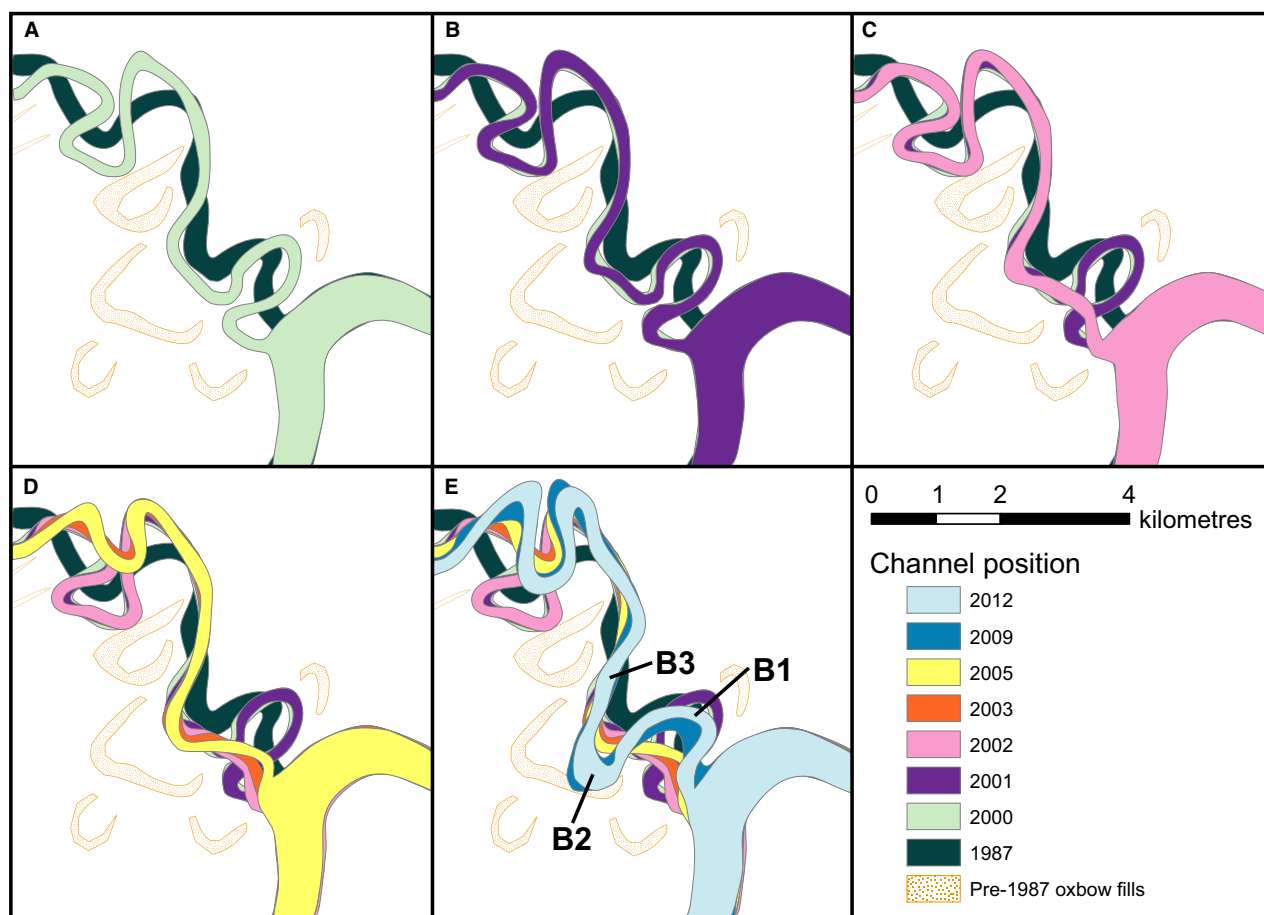


Fig. 2. Maps of channel evolution at the study site, based on 1987 to 2012 Landsat imagery, with the locations of Bends 1, 2 and 3 highlighted.

per slope that can detect small changes in the acoustic impedance. These features result in an excellent vertical resolution of the order 0.15 m, making it equivalent to ground-penetrating radar surveys conducted with 100 MHz antennae (a typical frequency used in many studies of coarser-grained river deposits). The results reported herein were obtained using a primary frequency of 100 kHz and a secondary frequency of 8 kHz. A Leica System 1230 real-time kinematic differential GPS (Leica Geosystems, St Gallen, Switzerland) was used for positioning, with a base station being set up on the bank, and a rover unit attached directly above the PES transducer to provide an overall accuracy of ± 0.02 m. The PES surveys were run using GlobalMapper software (Blue Marble Geographics, Hallowell, ME, USA) for plotting of position and track lines, with the Innomar PES providing data collection.

Tests showed that data collected when surveying in a downstream direction were of poor

quality and low resolution due to the vessel speed, as compared to data collected more slowly travelling against the current. The survey data reported herein comprise three lines taken broadly parallel to one another on the inside, centre and outside of the channel, and complemented by one line that repeatedly crossed these three lines to allow surfaces to be correlated (Fig. 3A). The data set thus comprises >25 km of PES survey lines. Data were converted to SEG Y format using Innomar ISE software, with subsequent visualization and interpretation undertaken in Kingdom[®] software. It should be noted that not all survey lines provided useable data, and most data collected in flow depths >7 to 8 m resulted in zero or limited data (Fig. 3B); this may be due to the additional engine noise required to pilot the boat in deep sections near the bank where very strong currents were encountered. Parametric echosounder surveys were conducted in late February and early

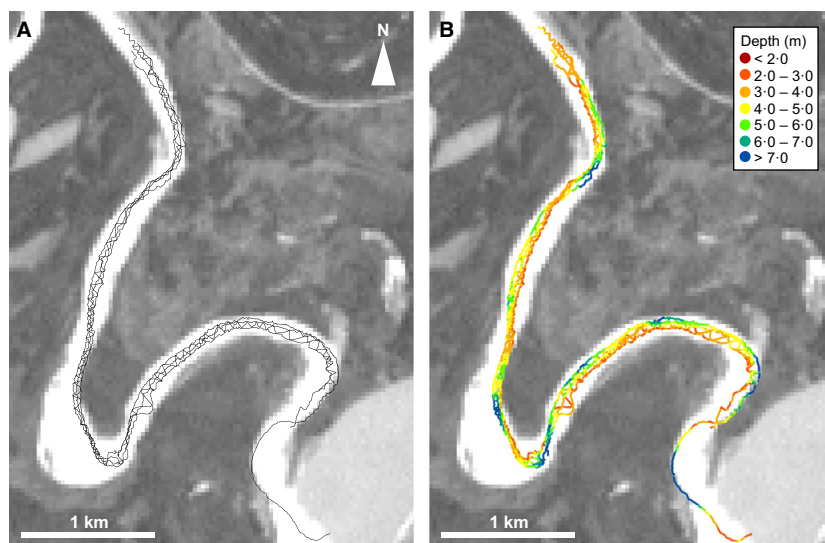


Fig. 3. (A) Trackplot of the parametric echosounder (PES) survey lines acquired around the three bends studied. (B) Plot of flow depth along the PES survey lines. Most of the PES data collected in depths >7 m (i.e. blue colour) were not useable.

March 2012 when flow stage peaked at ca $1500 \text{ m}^3 \text{ s}^{-1}$.

Coring and trenching

To provide context for interpretation of the PES data and information on the deposits at a higher resolution than the PES, a coring and trenching programme was undertaken at low flow (discharge ca $35 \text{ m}^3 \text{ s}^{-1}$) in November 2012 (Fig. 1). Five Van der Staay suction cores (Reesink *et al.*, 2014) were taken close to the PES lines along point bars and concave-bank benches. The cores were 0.08 m in diameter, and the depth of penetration and retrieval ranged between 1.4 m and 4.9 m, with the total length of the five cores being 17.6 m (i.e. an average of ca 3.5 m). The length of the longest cores was thus equivalent to the average penetration of the PES surveys. The cores were sawn in half lengthways on site

and photographed and logged. Fifty-two sediment samples were collected to calibrate the logs, and were later analysed using a Malvern Laser Mastersizer 2000 (Malvern Instruments Limited, Malvern, UK) to determine their grain-size distribution. In addition, several shallow trenches were dug where the cores were recovered in order to characterize the bar surface sediments, as well as at two bank sections that recorded the deposits of bank slumping and channel fill.

Suspended sediment

The distribution of suspended sediment within the river was measured at three cross-sections in Bend 1 (Fig. 1) during high flow in February/March 2012 (Fig. 4). At each cross-section, two verticals at 0.25 and 0.75 of the channel width, were sampled. For each vertical, suspended sed-

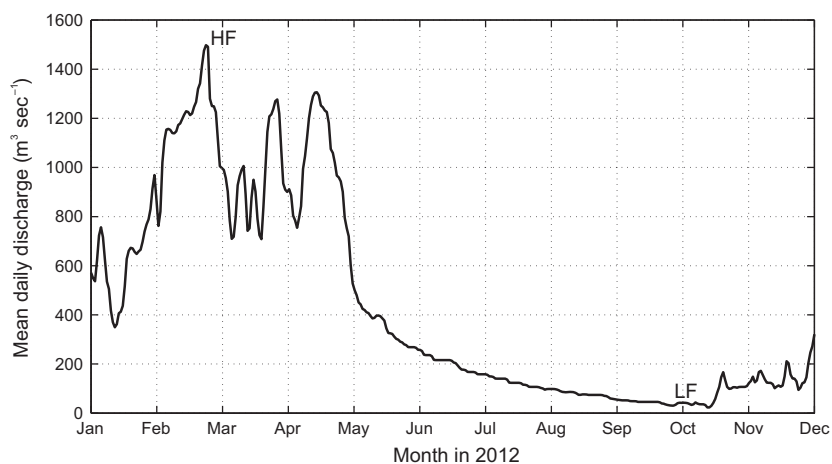


Fig. 4. Mean daily discharge for the Río Bermejo in 2012, with the time of the high (HF) and low flow (LF) surveys indicated.

iment samples were taken using an instantaneous suspended sediment sampler (Van Dorn bottle) at: (i) 0.5 m below the water surface; (ii) 50% of the total depth; and (iii) 0.5 m above the river bed, thus yielding a total of 18 samples. In the laboratory, each sample was filtered using a 62 μm pore size mesh, to retain the sand fraction. The <62 μm load concentration was analysed by filtering the subsamples using cellulose acetate discs with a 0.45 μm pore size. These samples were also analysed using a Malvern Laser Mastersizer 2000 to determine their grain-size distribution.

RESULTS

Bed material and suspended sediment load

Based on grain-size analysis of the cores and trenches, the bed surface of the Río Bermejo within the study reach varies between almost exclusively silt with a D_{50} of 8 to 25 μm up to one largely of fine and very fine sand with a D_{50} of 107 to 182 μm . Overall, the bed may thus be classed as sandy silt, as was also found by Iriondo & Orfeo (2012). This grain size is comparable with the lower reaches of the Huanghe River, China (for example, near Lijin), where D_{50} is typically 80 μm (e.g. Wang & Li, 2011) with *ca* 70% sand, 30% silt and very little clay (e.g. Li *et al.*, 1998). Based on all samples, the mean concentration of total suspended sediment was 22.5 g L^{-1} . There is a strong vertical gradient with values of 11.5 g L^{-1} near the water surface increasing to 74.6 g L^{-1} near the river bed. Concentration was also higher on the shallower inner right bank near the point bar, 26.6 g L^{-1} on average, as compared with the deeper, eroding outer left bank, that was 18.3 g L^{-1} on average. In terms of average suspended sediment concentrations over a year, these have been measured as 7.3 g L^{-1} (Ritter, 1977). Note that while these are very high concentrations, they are still an order of magnitude lower than reported from the Huanghe River, where average and maximum concentrations over a year may be 26 g L^{-1} and 220 g L^{-1} , respectively. Based on the samples taken at 50% of the flow depth, the suspended sediment of the Río Bermejo comprises 14% sand, 66% silt and 21% clay. For comparison, surface samples of the lower Huanghe River at Lijin have suspended sediments that comprise 12% sand, 79% silt and 9% clay (Li *et al.*, 1998).

Facies description

From the PES surveys, and allied coring and trenching, four principal depositional facies can be characterized within the Río Bermejo (Table 1).

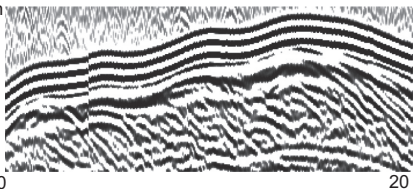
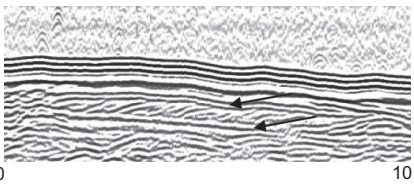
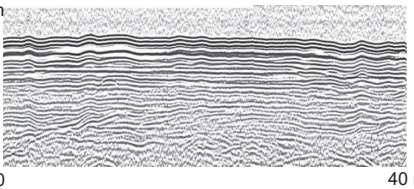
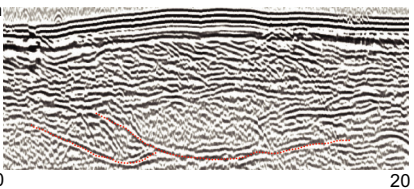
Facies 1 is characterized by thin (*ca* 0.5 m) upstream-dipping parallel reflections (Table 1) that may extend for up to 100 m in length. This facies is almost exclusively found in the upper 1 to 2 m of the sediments and the reflections may dip at a high angle.

Based on observations from cores, trenches and cutbanks at low flow, this facies is interpreted as small-scale sets related to deposition associated with climbing ripples. These reflections are the result of ripples that migrate downstream but, as the rate of sediment aggradation increases, possibly on the falling limb of the hydrograph, begin to climb, with ripple aggradation sometimes being almost vertical. Trenches and cutbanks revealed numerous examples of this type of deposition with pronounced grain-size and density sorting in the leeside of the ripples (Fig. 5), where slightly finer sediment and organic fragments are very distinctive in appearance. It is this grain density/size contrast that is picked out in the PES surveys, producing an upstream-dipping surface from the leeside of a highly aggrading, but downstream-migrating, series of current ripples (Fig. 5). The presence of climbing ripples with such steep angles of climb (some being greater than the angle-of-repose of the sediment and up to 70 to 80°) is indicative of very high rates of aggradation from the exceptionally high suspended sediment concentrations present in the Río Bermejo as the flow stage drops. For instance, as shown above, *average* values of total suspended sediment load at the time of the high flow PES surveys were >20 g L^{-1} .

Facies 2 is characterized by thin (<0.5 m), downstream-dipping parallel reflections, typically <50 m in length. These reflections can be present at any depth in the profile, but where they are present lower down in the sediments (i.e. not at the bed surface), the parallel-dipping reflections appear as stacked bed sets with a low-angle bounding surface between them (Table 1). Occasionally, these downstream-dipping reflections possess a more sigmoidal reflection geometry (Fig. 6).

Based on observations at low flow, this facies is interpreted to represent medium-scale (*ca* <0.5 m high) bed sets associated with the migration of dunes or possibly small bars. The down-

Table 1. Examples, descriptions and interpretations of the primary parametric echosounder (PES) facies reported in this study.

Example	Description	Interpretation
	Facies 1: <i>ca</i> 0.5 m thick upstream-dipping parallel reflections that may extend for up to 100 m in length. Typically found in the upper 1 to 2 m of the sediments, with reflections that may possess a dip angle greater than the angle-of-repose.	Small-scale sets associated with climbing ripples.
	Facies 2: <i>ca</i> 0.5 m thick downstream-dipping parallel reflections, typically <50 m in length. May be present at any depth and typically appear as stacked sets with a low-angle bounding surface between them (see arrows).	Medium-scale sets associated with dune or small bar deposition.
	Facies 3: Long (<i>ca</i> 100 m) parallel reflections that can be up to 3 m thick. Reflections either horizontal (usually at surface) or have a low angle of dip (<3°, usually lower down in profiles).	Large-scale sets associated with point-bar sedimentation. Inclined reflections typically relate to point-bar lateral accretion surfaces.
	Facies 4: Concave cross-cutting reflection with variable reflections within.	Channel cut/fill related to cross-bar channels (<i>ca</i> 0.5 m thick) or basal scour of main channel (up to 5 m thick).

stream-dipping parallel reflections represent the preserved foresets of migrating dunes and small bars, such as those that are present on exposed bar surfaces at low flow (Fig. 7). Reflections that are predominantly downstream-dipping, but possess a more sigmoidal reflection pattern, are also associated with dunes, and reflect cases where a greater proportion of the internal sedimentary structure has been preserved rather than just the base of the foreset. For example, the reflection pattern seen in the lower part of Fig. 8 is interpreted to relate to dunes migrating up a point-bar surface, with both the foreset and part of the dune topset being imaged by the PES. Sediment samples taken from dunes at low flow indicate that these downstream-dipping reflections are probably found where the bed material comprises well-sorted fine to medium sand but with an absence of silt (for example,

$D_{10} = 121 \mu\text{m}$, $D_{50} = 182 \mu\text{m}$ and $D_{90} = 271 \mu\text{m}$). It is also worthy of note that the suspended sediment samples show that significant quantities of sand-size material are in transport at 0.5 m above the bed, with this size fraction comprising up to *ca* 65% of the total load in places. Silt size sediment dominates higher up in the flow and away from the bed, but the presence of sandy bedforms in this silt-dominated river is clearly important for the generation of bed topography.

Facies 3 is represented by long (*ca* 100 m) parallel reflections that can be up to 3 m thick (Figs 8 and 9; Table 1). These reflections typically are either horizontal or have a low angle of dip, typically <3° with a maximum of 8°, with the dip orientations covering a wide range from upstream through to downstream. Horizontal reflections are most commonly found in the upper part of the profile, while dipping reflec-



Fig. 5. Photograph of climbing ripple cross-stratification exposed in cutbanks, showing a very high angle of climb. Flow is from left to right, with tape measure being *ca* 0.7 m long. The thickness of the lower set of climbing ripples, deposited in one decelerating flow event, is *ca* 0.5 m.

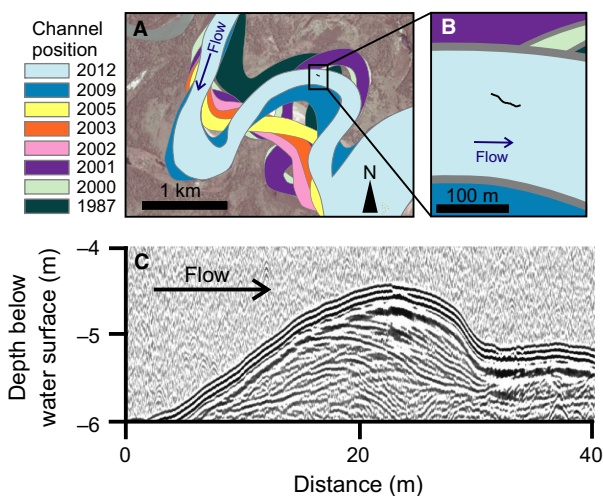


Fig. 6. Location of the parametric echosounder (PES) line within (A) the study site, and (B) the reach, that shows an example of (C) downstream-dipping reflections, with a sigmoidal shape, associated with dune migration.



Fig. 7. (A) and (B) Dunes exposed at low flow at location 1 (see Fig. 1), with heights of <0.5 m and an average wavelength of 12 m. (C) Google Earth image from a section of the river just upstream of the study site showing dunes exposed at low flow. Image courtesy Google Earth, © DigitalGlobe.

tions are more usually located lower down in the PES profiles. These dipping reflections either have a consistent angle or occur in a more com-

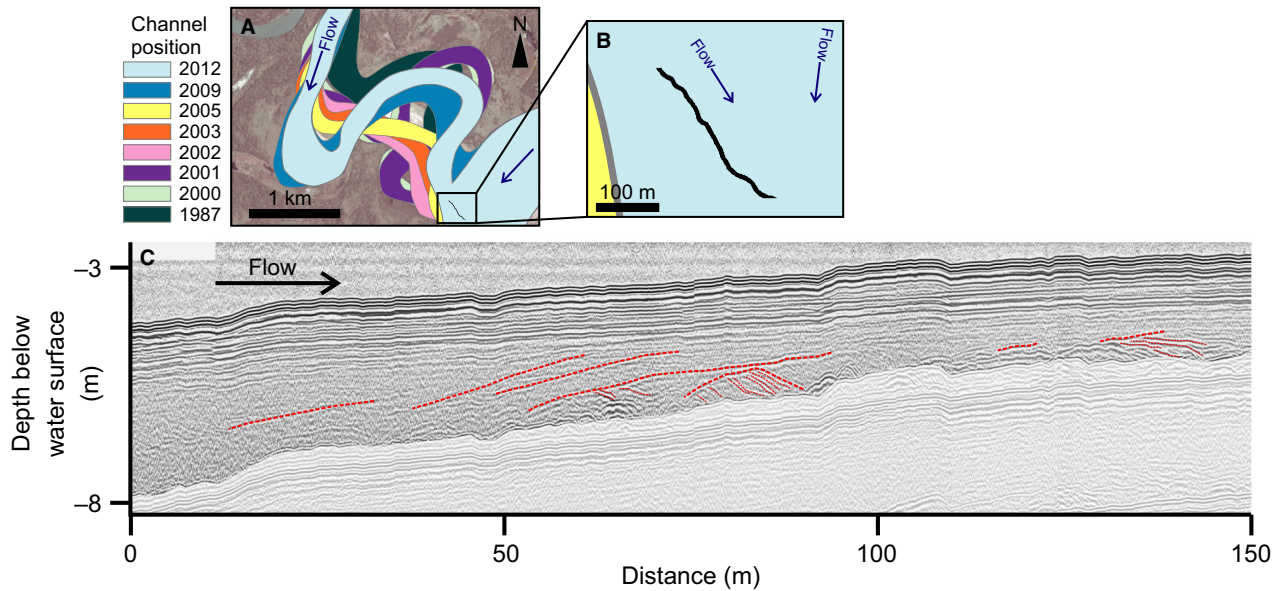


Fig. 8. Location of the parametric echosounder (PES) line within (A) the study site, and (B) the reach, that shows an example of (C) low-angle surfaces indicative of point-bar lateral accretion (facies 3). Between these lateral accretion surfaces, smaller and slightly steeper reflections are present that are probably related to dune migration (facies 2) onto the point bar. Some of the most evident reflections are indicated with red dashed lines, while reflections below the multiple have been shaded in light grey and should not be considered.

plex assemblage where, for example, one set of reflections may onlap with another that is orientated in a different direction (Fig. 10). These dipping reflections often display truncation towards their top where an erosion surface may be present.

This facies is interpreted as being the product of large-scale sets associated with point-bar sedimentation. The large sets of parallel, horizontal reflections found near the surface are interpreted as fine-grained deposition from suspension under relatively quiescent conditions, certainly as compared with the climbing ripples of facies 1. Such facies 3 deposits were thus likely to be associated with low shear stresses and low flow stages on submerged bar surfaces. The dipping reflections of facies 3 have a different origin, and are interpreted as lateral accretion surfaces often associated with point-bar deposits (Fig. 11), or what has also been termed ‘inclined heterolithic stratification’ (IHS; Thomas *et al.*, 1987). Facies 3 thus records the episodic movement of the highly active meanders of the Río Bermejo, with most of the dipping reflections terminating before the top 1 to 2 m of sediment that is characterized by another facies. Indeed, some of the PES panels allow the three-dimensional shape of these surfaces to be mapped (Fig. 12) and reveal a series of gently inclined

surfaces that decrease in angle, both into the deeper part of the profile as well as towards the bed surface (i.e. they have a sigmoidal profile). These images also show the upper surface to become shallower in angle in successive stacked low-angle reflections, probably reflecting the lower-angle upper point-bar surface as the bend migrated through this volume.

Cores and trenches taken at the point bars in Bends 1 and 3 reveal some of the smaller scale sedimentary structures associated with facies 3 (Figs 13 and 14), including sub-horizontal to steeply dipping silty laminae, ripple-scale cross-sets, mud clasts, desiccation cracks (due to drying out of the bar tops at low flow), dewatering/fluidization structures that are easily formed in such fine-grained sediment, symmetrical ripples generated through sediment reworking by wind-driven surface waves and decimetre-thick silt layers, the latter being found at the top of the succession. All of these sedimentary structures appear to be characteristic of fine-grained rivers with a high suspended load that have pronounced wet and dry seasons. The cores also reveal an appreciable down-bar fining around these point bars, similar to grain-size fining seen in sand-bed and gravel-bed meandering rivers. Very fine sands become dominant at the down-flow end of the point bar, with medium-fine

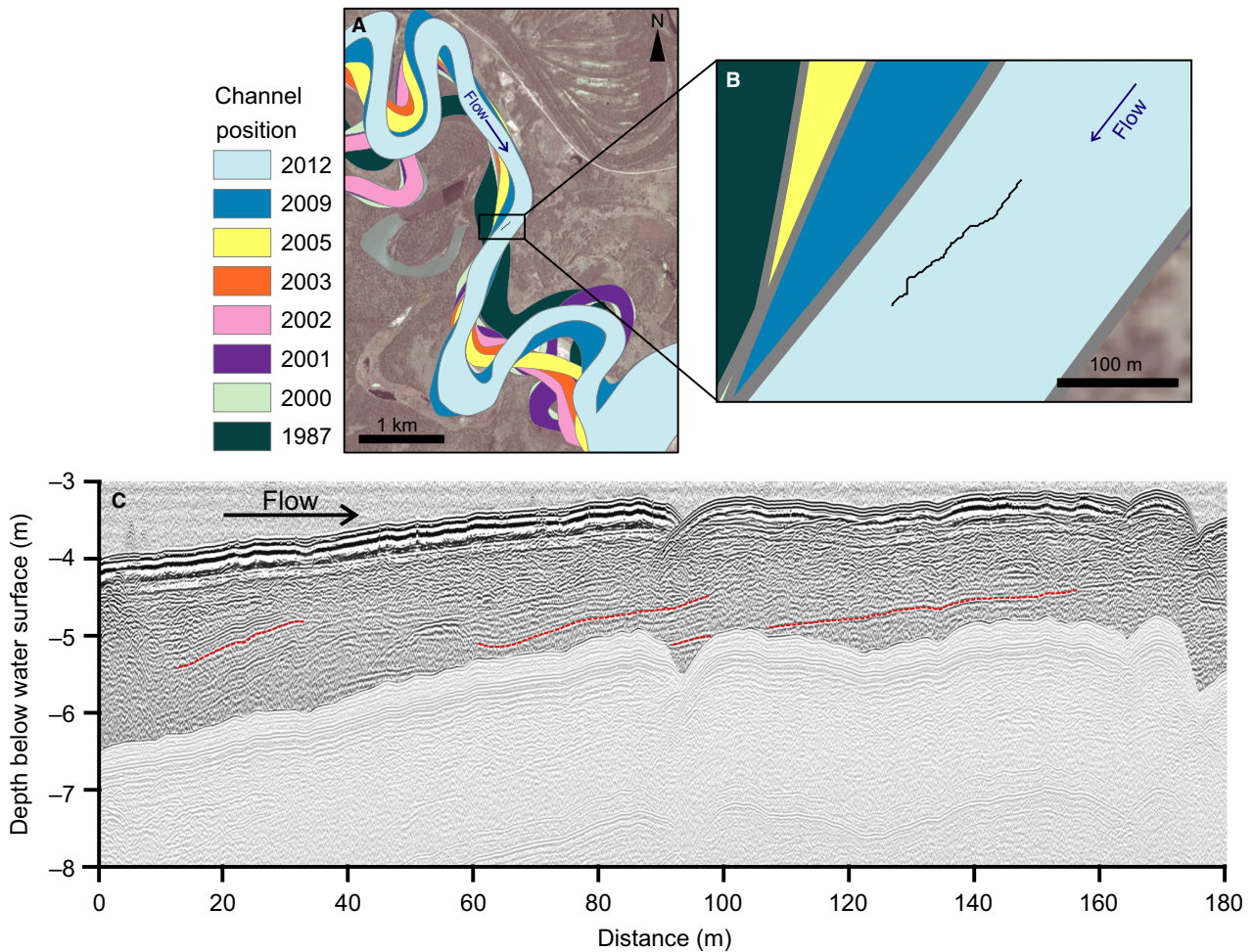


Fig. 9. Location of the parametric echosounder (PES) line within (A) the study site, and (B) the reach, that shows an example of (C) facies 3 that is interpreted as inclined heterolithic stratification (IHS) associated with point-bar migration. Some of the most evident reflections are indicated with red dashed lines, while reflections below the multiple have been shaded in light grey and should not be considered.

sands only being present in the bottom 0.8 m of the core at these down-bar locations (Fig. 13, cores 5 and 6.)

Facies 4 displays a range of concave reflections (Table 1), that are simply subdivided by thickness into those that are smaller (<0.5 m thick; Fig. 15) and larger (up to 5 m thick; Fig. 16). The defining characteristic of this facies is the outermost concave reflection that displays a clear cross-cutting relationship with the reflections below. However, the internal character of the reflections above this outer concave surface is highly variable between the different examples imaged in the surveys. The smaller examples of facies 4 are typically found towards the bed surface, while the larger concave reflections are found deeper in the sections.

The small concave reflections are interpreted herein as cross-bar channels that may be located at the edge of bars (Fig. 17A). These small channels may grow by headward erosion across the bar as flow stage drops, and in this case are widest at the bar edge and become narrower towards the bar top. Alternatively, Landsat images show that these channels can form small dendritic networks across the exposed bar surfaces (Fig. 17B and C). When compared with ground-penetrating radar surveys and aerial imagery from sand-bed rivers, these small cross-bar channels appear very commonly in the Río Bermejo, possibly due to the finer grain size and cohesiveness of the sediments, which may favour erosion of such small channels.

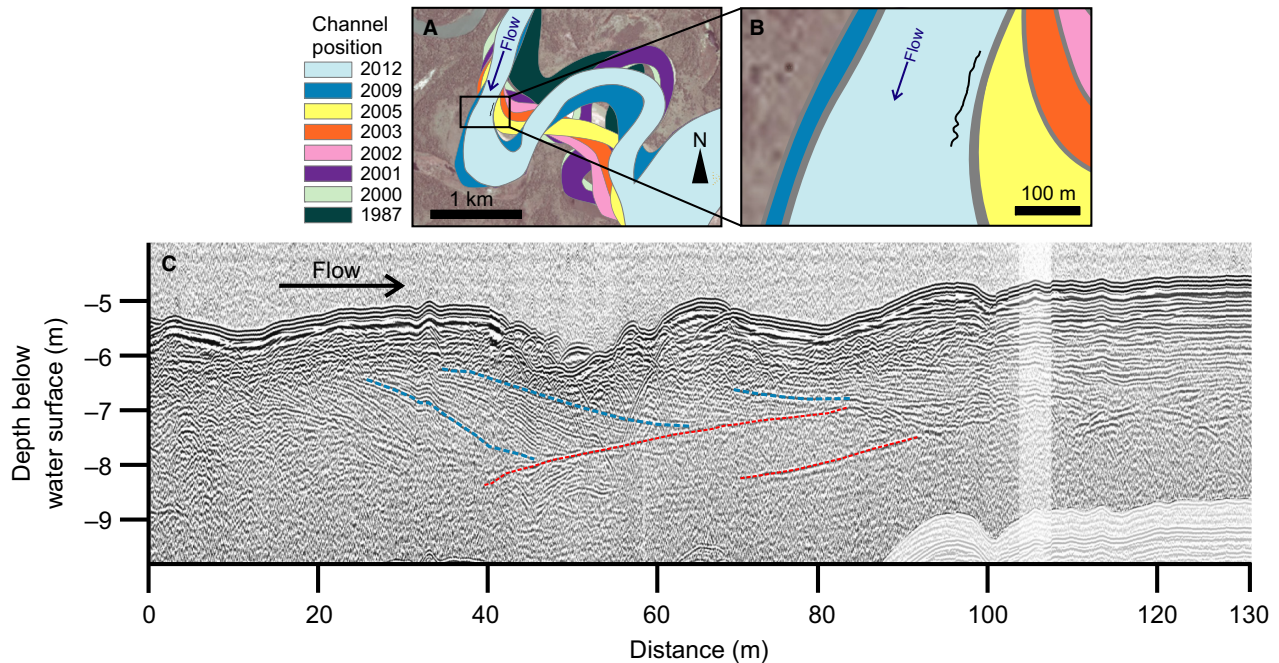


Fig. 10. Location of the parametric echosounder (PES) line within (A) the study site, and (B) the reach, that shows an example of (C) two sets of facies 3 (low-angle surfaces indicative of point-bar lateral accretion) orientated in different directions. Those highlighted in blue are orientated downstream and relate to migration of the point bar on the inside of Bend 2. Those lower down marked in red may relate to a previous point bar when the channel was in a different position to that shown in (A). Some of the most evident reflections are indicated with red dashed lines, while reflections below the multiple have been shaded in light grey and should not be considered.



Fig. 11. Extensive low-angle surface typical of point bars on the Río Bermejo, Bend 1 (see Fig. 1 for location). The point-bar surface typically has a finer silty drape, in which extensive desiccation cracks are developed, and that may indicate deposits at the end of each flood season, as seen in the cores shown in Fig. 13. This image was taken at low flow, with the channel flow width at this time being *ca* 100 m.

The large examples of this facies are inferred to relate to the cut and fill of the principal Río Bermejo channel as it migrates across its flood-

plain (Figs 1 and 2). The largest example of this facies is seen at Bend 2 (Fig. 16). Here, the scour is large, isolated, concave-upward and its base can be traced *ca* 12 m below the water surface at the time of survey, which is equivalent to the maximum channel depth surveyed at this bend. Bend 2 has been in a similar position for approximately five years, during which it has widened and a concave-bank bench has formed (Fig. 2). The deep scour within the bend has thus probably moved location as the bend has grown, resulting in the reflection patterns revealed in the PES survey. This scour and its fill are similar to that related to eddy-accretion deposits described by Smith *et al.* (2011), who found such features typically forming at abrupt channel meanders where the bend is particularly resistant to erosion. The pre-1987 cut-off at the apex of Bend 2 may have acted to resist erosion at this point, thus resulting in the deep scour found here. Evidence for significant channel movement is also found within the cutbanks (Fig. 18), which display sections through what is interpreted to be a large channel margin, with associated slump blocks and fluidization. The

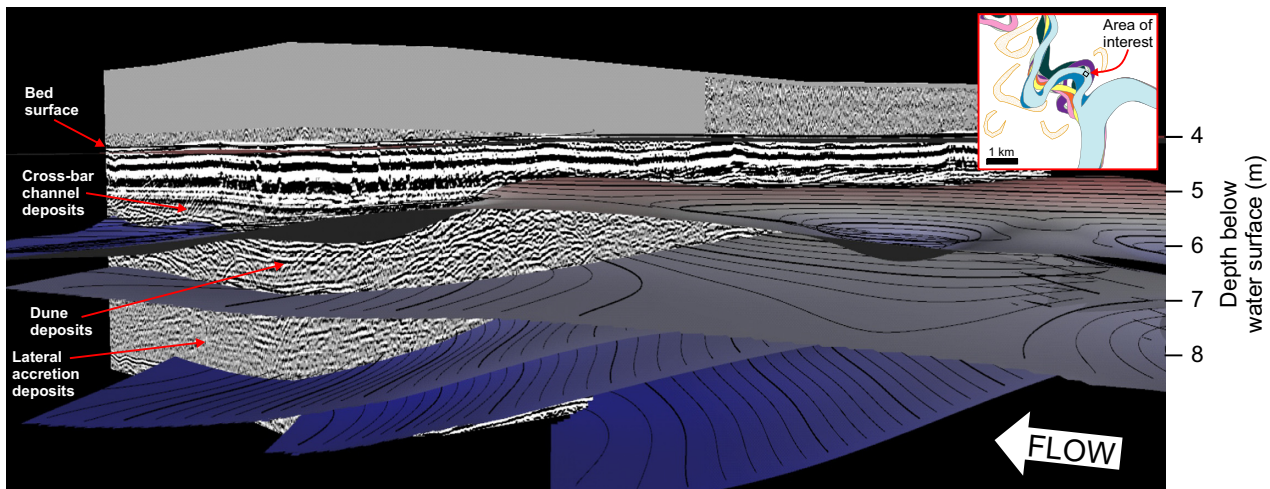


Fig. 12. Three-dimensional visualization, based on intersecting parametric echosounder (PES) survey lines, of an area $ca\ 100 \times 70\text{ m}$ over point-bar deposits in Bend 1 (see inset for location). At the base of the sequence, low-angle parallel-dipping reflections are associated with lateral accretion deposits of the point bar. Above this, medium-scale cross-strata associated with dune migration are present, and these have been eroded by a cross-bar channel that has subsequently been infilled (as shown by the curved surface of the traced reflection and infill above, as seen at the top of the image).

contemporary channel (Fig. 19) also displays marked slumping at the outer margins of the steep channel banks.

Summary of alluvial architecture

To provide an indication of the relative proportions of facies and the spatial relationships between them, four survey areas were selected for detailed analysis where there were several intersecting PES lines that allowed 3D visualization of the facies (for example, Fig. 12). This analysis shows a facies abundance of: Facies 1 – 3.6%; Facies 2 – 25.7%; Facies 3 – 65.9%; and Facies 4 – 4.8%. Overall, the deposits thus show domination by lateral accretion surfaces and low-angle smaller cross-sets produced by dunes and small bars. If just the top 2 m of deposits are considered, the facies distribution is: Facies 1 – 8.5%; Facies 2 – 46.4%; Facies 3 – 34.6%; and Facies 4 – 10.5%. This result confirms the observations above that facies 3 tends to dominate the lower sections of the point bars, with smaller sets associated with dunes and climbing ripples being more prevalent in the upper parts. As noted from aerial and ground imagery (Fig. 17), the upper bar deposits may be significantly reworked by cross-bar channels. In summary (Fig. 20), the deposits of the fine-grained Río Bermejo are characterized by a lower unit comprising lateral accretion surfaces and large-scale scour surfaces, with the deepest

scours likely to be associated with the most sinuous bends. These sediments typically are truncated and overlain by deposits that are smaller in scale and composed of vertical accretion deposits, cross-sets associated with small bars, low-angle dunes and climbing ripples, as well as the cut and fill from small cross-bar channels.

DISCUSSION

The data reported herein appear somewhat different to previous studies of modern fine-grained rivers. For example, Jackson (1981) described the fine-grained deposits of meandering rivers in the American mid-west. However, these channels are much smaller (i.e. widths $ca\ 10\text{ m}$) than the Río Bermejo, and probably not directly comparable because they have a significant influence from log jams, plant debris and mud blocks that do not appear to be influential in larger fine-grained rivers. Other studies have stressed the importance of oblique accretion (e.g. Gibling *et al.*, 1998; Page *et al.*, 2003; Marren *et al.*, 2006) as a dominant feature of the deposits of fine-grained rivers (Fig. 20). Page *et al.* (2003) define oblique accretion as: “the lateral accumulation of fine-grained floodplain sediment by progradation of a relatively steep convex bank in association with channel migration”. However, the Río Bermejo has a predominance of point bars within the channel and hence oblique

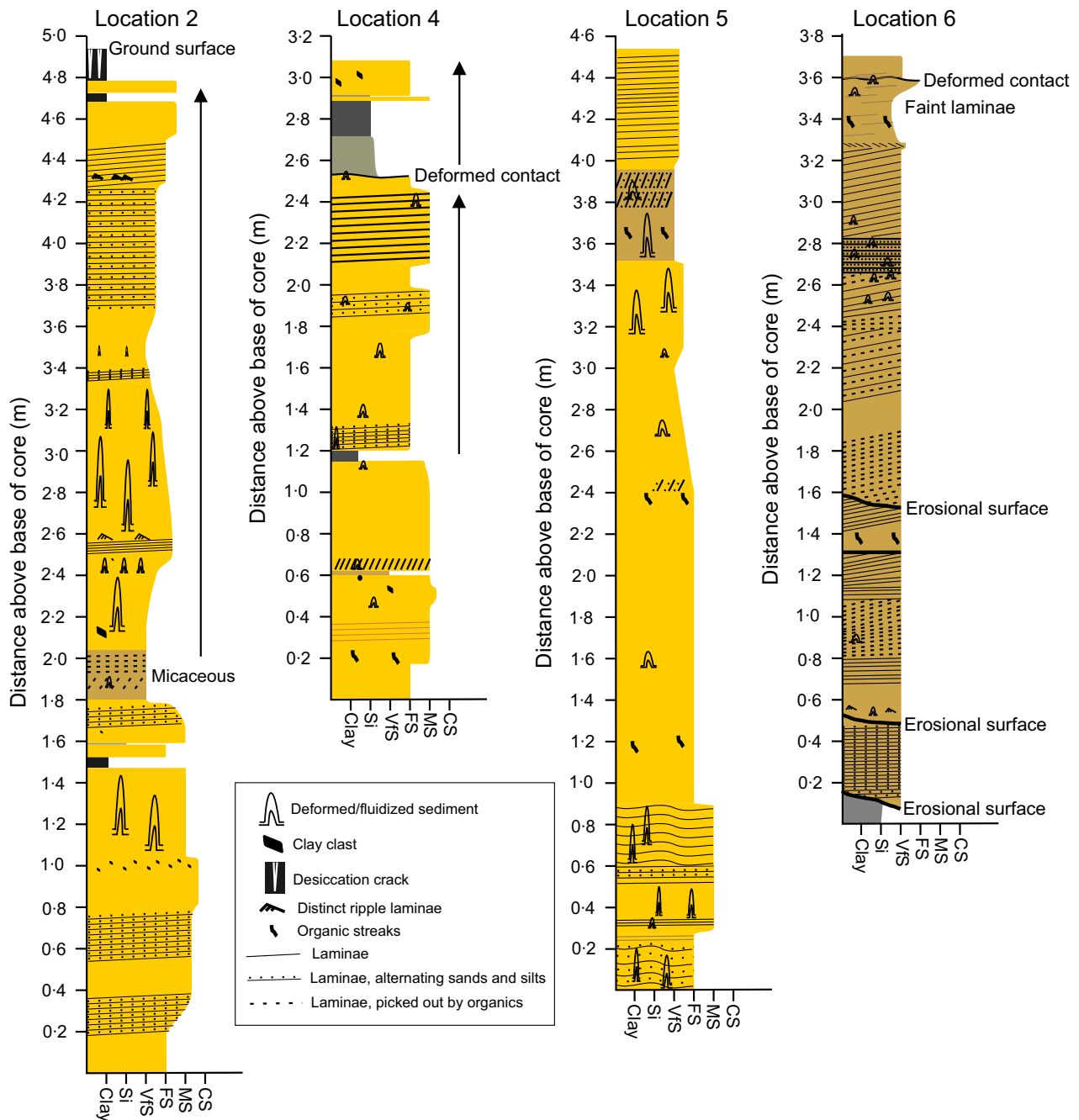


Fig. 13. Characteristics of cores taken from several bends in the study reach (see Fig. 1 for locations). Core locations 2 and 4 were taken from the upstream sections of point bars in Bends 3 and 1, respectively, while core location 5 was taken from the downstream section of Bend 1. Core location 6 was taken from a concave-bank bench in Bend 2. The vertical arrows indicate deposition interpreted as occurring during one flood season. Si = silt; VfS = very fine sand; FS = fine sand; MS = medium sand; and CS = coarse sand.

accretion is unlikely to be a dominant process. The angles of the large-scale inclined surfaces identified in the PES data are also much lower, typically $<8^\circ$, than those reported for oblique accretion, which is generally much higher because it represents drapes deposited on the

bank, with Page *et al.* (2003) citing values of 29° . Observations of bank failure on the Río Bermejo also indicate the dominance of slab failure (Fig. 19), with some of this material being preserved as slump blocks at one cutbank section (Fig. 18). However, many of the active channels

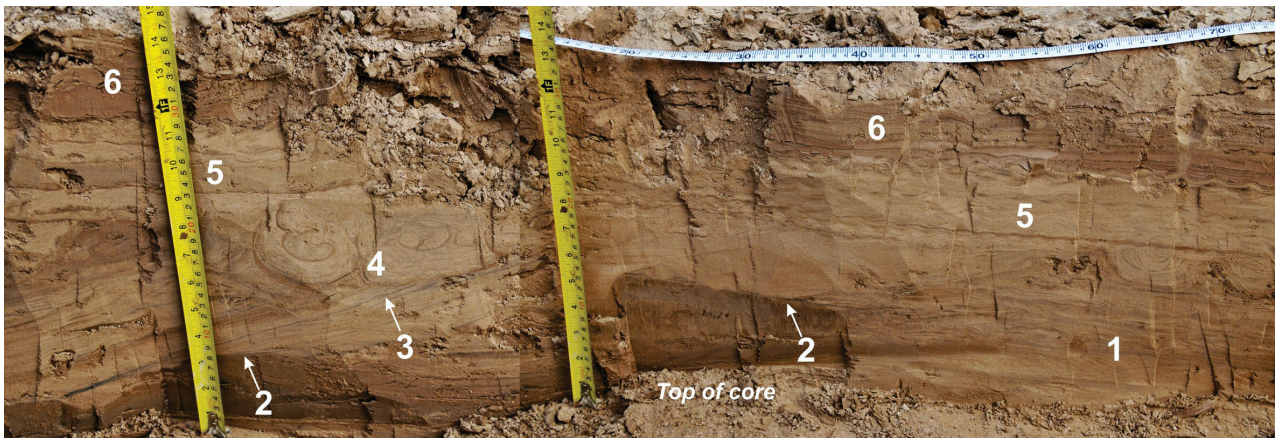


Fig. 14. Photomontage of a shallow trench at location 4 (see Fig. 1 for location), dug into the surface of the point bar at Bend 1. These sediments lie stratigraphically above the core taken from this location and shown in Fig. 13. Labels denote: '1' – climbing ripples; '2' – bar surface with desiccation cracks; '3' – steeper angle accretion surface; '4' – deformed/liquefaction horizon; '5' – fine sand and silt with symmetrical wave ripples; '6' – decimetre-thick silt layer deposited at the end of the flood season. Depth of trench *ca* 0.4 m.

appear to quickly erode their slump blocks and the PES bottom elevations revealed no intact slump blocks in any of the bends surveyed. It thus appears that the grain size (i.e. less cohesive silt dominates as opposed to cohesive clay) and high flow velocities of the Río Bermejo result in slump block preservation being relatively rare. There was also no direct evidence in the Río Bermejo for the large rotational slumps described by Brooks (2003) in the Red River, Manitoba.

Useful comparisons can also be made with descriptions of ancient fine-grained rivers, the studies of which are not restricted to just small cutfaces or cores. In a study of the Lower Permian (Wolfcampian) Abo Formation of south-central New Mexico, Mack *et al.* (2003) describe the deposits of a silty river. The two primary within-channel depositional styles detailed by Mack *et al.* (2003) are: (i) inclined strata, interpreted as relating to point-bar accretion (similar to facies 3 herein); and (ii) erosive, convexo-concave beds that defined broadly symmetrical, sharp-based, channel forms interpreted as relating to migrating channels (similar to facies 4 herein). The dominant smaller scale bedforms documented by Mack *et al.* (2003) were climbing ripples and upper-stage plane beds. Mack *et al.* (2003) interpreted these Permian sediments as being deposited in an active meandering river with channel dimensions *ca* 5 m deep and 40 m wide. The broad alluvial architecture described by Mack *et al.* (2003; see fig. 7) thus bears many similarities to that presented herein for the Río Bermejo, although Mack *et al.* (2003) note the rarity

of cross-beds associated with dunes in the deposits, suggesting that these Permian rivers were more fine-grained than the Río Bermejo. The finer, more cohesive sediments of the Abo Formation may also explain the higher angles recorded for their lateral accretion surfaces; the Mack *et al.* (2003) study reported minimum values of 8°, which represents the maximum recorded for the Río Bermejo.

The potential role of grain size in controlling the angle of lateral accretion surfaces can be found in the work of Edwards *et al.* (1983) in a study of fine-grained point-bar deposits in the Clear Fork Group (Lower Permian) of north-central Texas. Edwards *et al.* (1983) report that where sandstone and siltstone beds are intercalated, which is the situation most similar to the Río Bermejo, the accretion surfaces have dips of 5° to 8° that are similar to those recorded herein. However, where sand is largely absent and mudstone predominates, Edwards *et al.* (1983) found dips that were much higher (15° to 25°) and similar to those recorded by Mack *et al.* (2003), also largely in a sand-free environment. The deposits described by Edwards *et al.* (1983) also show strong evidence of highly seasonal flow with large changes in stage, with erosion of point bars by small cross-bar channels as stage drops. Again these are features that are also shared by the deposits of the Río Bermejo.

Lastly, another directly comparable ancient example is that found in the Lower Cretaceous Wealden Group of Southern England. The alluvial architecture in these sediments was

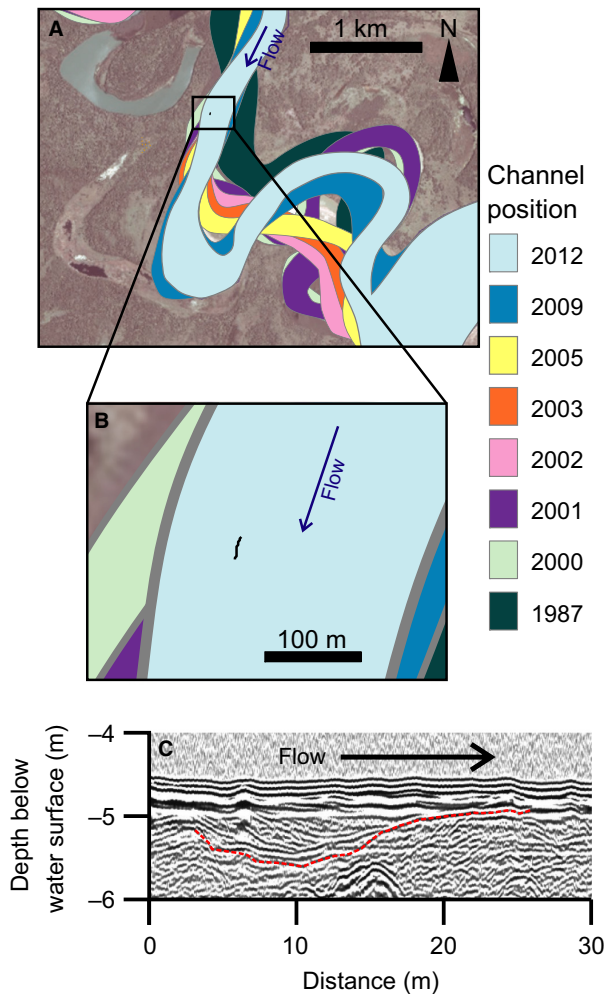


Fig. 15. Location of the parametric echosounder (PES) line within (A) the study site, and (B) the reach, that shows an example of (C) a small channel cut and fill (facies 4).

described by Stewart (1981, 1983) and shows point-bar deposits with a much greater variability in sand content than those deposits documented herein, although grain-size did decrease from barhead to bartail as found in the Río Bermejo. The point-bar deposits described by Stewart (1981, 1983) also possess a diverse range of grain sizes and sedimentary structures, including abundant climbing ripples that are indicative of high suspended sediment loads and that are a common feature of bar-top deposition in the Río Bermejo. Further similarities between the Lower Cretaceous sediments and those of the Río Bermejo are the abundant deformation structures and desiccation cracks. The Wealden Group point bars were interpreted by Stewart (1981, 1983) as having been formed in a warm temperate subtropical climate, again simi-

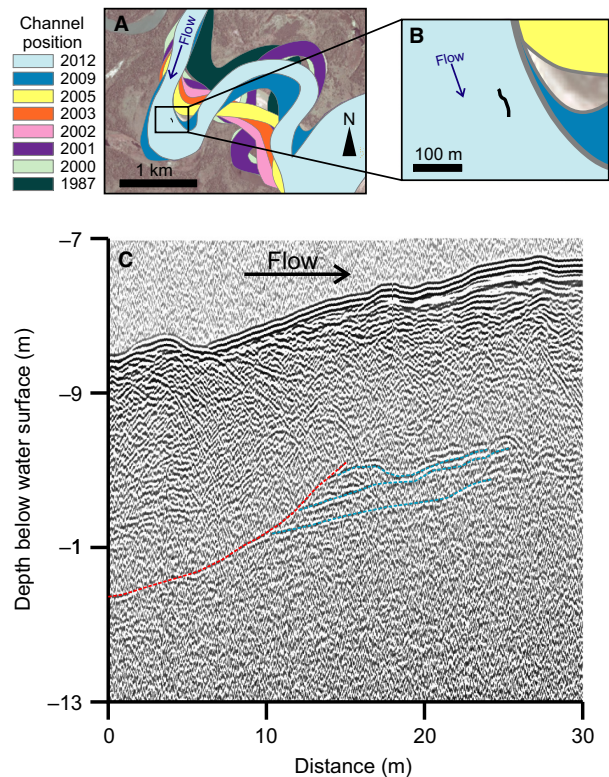


Fig. 16. Location of the parametric echosounder (PES) line within (A) the study site, and (B) the reach, that shows an example of (C) cut and fill of the scale of the main channel (facies 4). The red line shows an erosion surface truncating the adjacent deposits (highlighted in blue).

lar to the Río Bermejo with its pronounced wet and dry seasons.

An important point highlighted by both Stewart (1981, 1983) and Mack *et al.* (2003) is that the deposits studied indicated channels that were *actively* migrating, with rapid migration of point bars and frequent meander cut-offs. While not explicitly stated, it can also be inferred that the meanders detailed by Edwards *et al.* (1983) were also active because values of the ratio of the radius of curvature to channel width of 3 to 4 were recorded. This value falls within the 2 to 4 range that is commonly accepted to correspond to maximum rates of lateral meander migration. Furthermore, both the work of Stewart (1981, 1983) and Mack *et al.* (2003) stressed how silt dominates the deposits, not because of downstream-fining leading to deposition in a distal system but because silt dominates the size of sediment supplied to the basin. The evidence from the Río Bermejo presented herein supports such interpretations, and highlights the control by the local sediment supply.



Fig. 17. (A) Example of cross-bar channels seen in Google Earth image at Bend 2 (see Fig. 1 for location). The black arrows point to channels extending by headcut erosion on the inner bend, while the blue arrow points to similar channels formed on the outer bend concave-bank bench. (B) Google Earth image showing dendritic channels extending by headcut erosion (arrowed) from a reach upstream of the study site. (C) Ground view of a cross-bar channel at Bend 3 (see Fig. 1 for location) taken at low flow, that cuts across the point-bar surface and is imaged by the parametric echosounder (PES) (facies 4, Fig. 15, Table 1). Images courtesy Google Earth, © DigitalGlobe.

fine-grained river such as the Río Bermejo. As discussed by Stewart (1983), if only a limited vertical exposure of deposits is available, then such deposits could easily be interpreted as relating to the floodplain or a crevasse splay, because the lateral exposure necessary to identify a point bar is absent. Once again, the data presented herein wholly support this argument, and the PES data suggest that only large-scale exposures would reveal the shallow angle of the point bars.

The new data presented herein and examples discussed above serve to highlight that fine-grained rivers have a high degree of diversity in their dominant processes and resultant sedimentology. For simplicity, herein it is proposed that fine-grained meandering rivers (braided systems are not considered herein) will lie on a continuum between two end-member states (Fig. 20): (i) those dominated by oblique accretion; and (ii) those dominated by lateral accretion associated with point bars. Both of these river types have many similar features, in that they transport a significant fine-grained load and possess a distinct seasonality in their discharge regime. However, it is suggested here that it is the specific combination of grain-size distribution (for example, the relative proportions of fine sand, silt and clay) together with the suspended sediment concentration that will determine the resultant sedimentology. Thus, rivers with slightly coarser (for example, fine sand and silt, with no clay) and larger volumetric suspended sediment loads will lead to lateral accretion deposits being dominant, while finer (mainly clay) and lower volumetric suspended sediment loads will lead to the dominance of oblique accretion deposits. In the former case, the presence of a small proportion of sand will lead to the generation of low-angle migrating dunes,

The relevance of this issue is that silt-grade fluvial deposits are often assumed to be indicative of a quiescent type of sedimentary environment (Gruszka & Zieliński, 2008), yet this would be an erroneous interpretation for a highly active

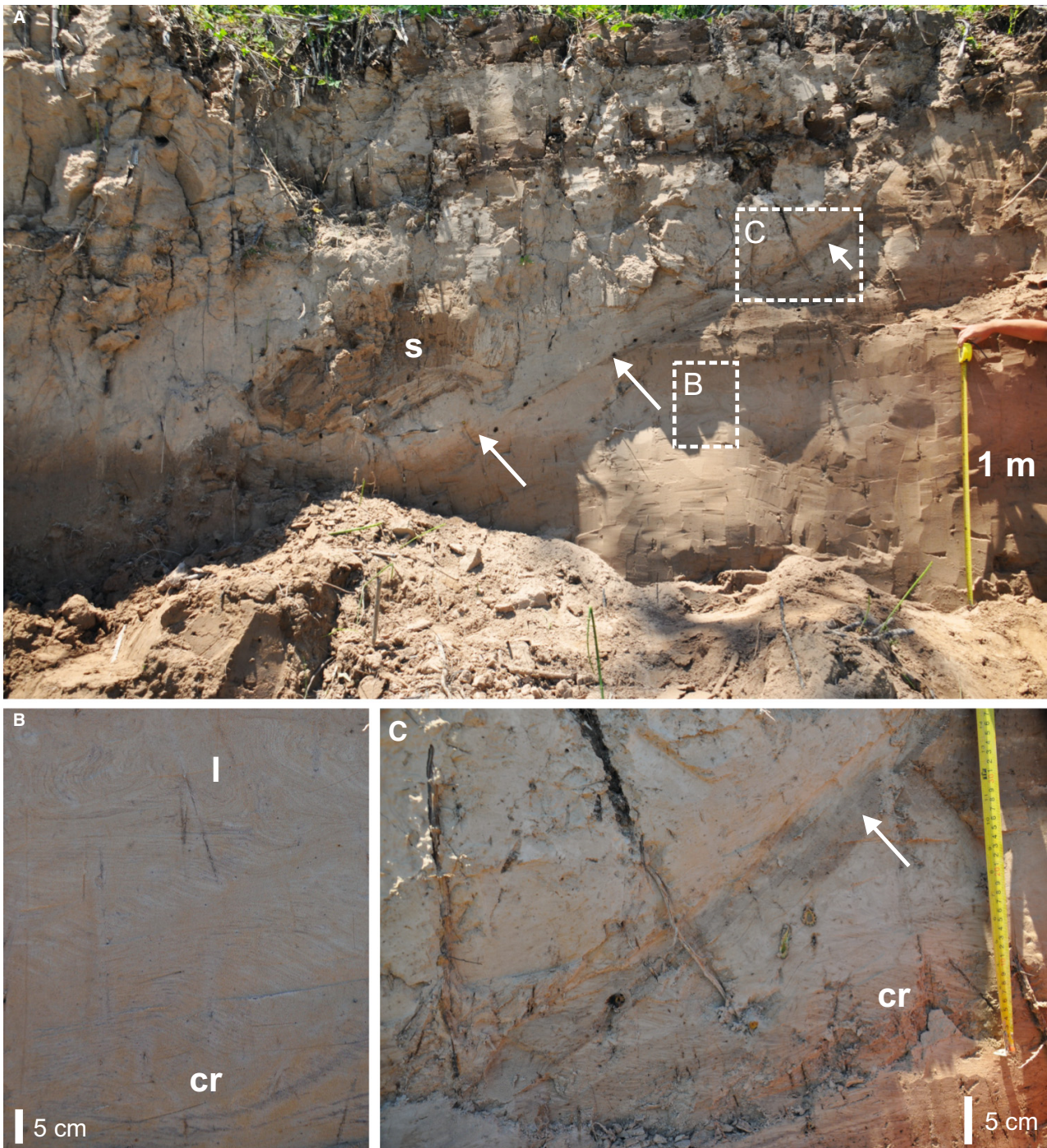


Fig. 18. A large-scale channel cut and fill exposed in a cutbank at location 7 (see Fig. 1 for location). White arrows point to channel margin; 's' – slump block; 'cr' – climbing ripples; 'l' – liquefaction horizon; Dotted outline boxes in (A) denote areas of images shown in (B) and (C).

from which point bars may develop (for example, see Figs 7 and 8). If these point bars are subject to 0.5 to 1.0 m of vertical accretion as flow stage drops (for example, Fig. 14), then during the subsequent high flow season this accumulated mate-

rial will act to deflect flow against the opposite bank, driving bank erosion and channel migration (and hence further point-bar development) in what has been termed 'bar push' (Parker *et al.*, 2011). Conversely, where suspended sediment



Fig. 19. Image taken at low flow of slump blocks at the base of a channel bank at the outside of a meander bend. Observations at high flow stage indicate that these blocks are short-lived and become readily eroded. Person for scale is *ca* 1.8 m tall.

loads are lower and finer grained, there are fewer large-scale bedforms and the material is simply draped onto the channel banks in thin layers as flow stage drops. This results in cohesive banks

and in the slow rates of overall channel migration, and hence results in the dominance of oblique accretion. Between these two end members will lie a continuum of differing sedimentological characteristics. For example, as discussed herein, as the fine sand diminishes within a river this may lead to steeper accretion surfaces being preserved. A full conceptual understanding of how subtle differences in the proportion of silt and clay may change processes, and hence sedimentary product, remains to be elucidated. However, a growing body of work indicates that even relatively small concentrations of silt and clay can influence bedform dimensions and erosion thresholds (e.g. Law *et al.*, 2008; Baas *et al.*, 2009, 2011, 2015; Bartzke *et al.*, 2013; Schindler *et al.*, 2015).

CONCLUSIONS

Field study of the fine-grained, highly sinuous and actively migrating, Río Bermejo, Argentina, shows that its alluvial architecture is characterized by: (i) a lower unit comprising inclined lateral accretion surfaces and large-scale scour

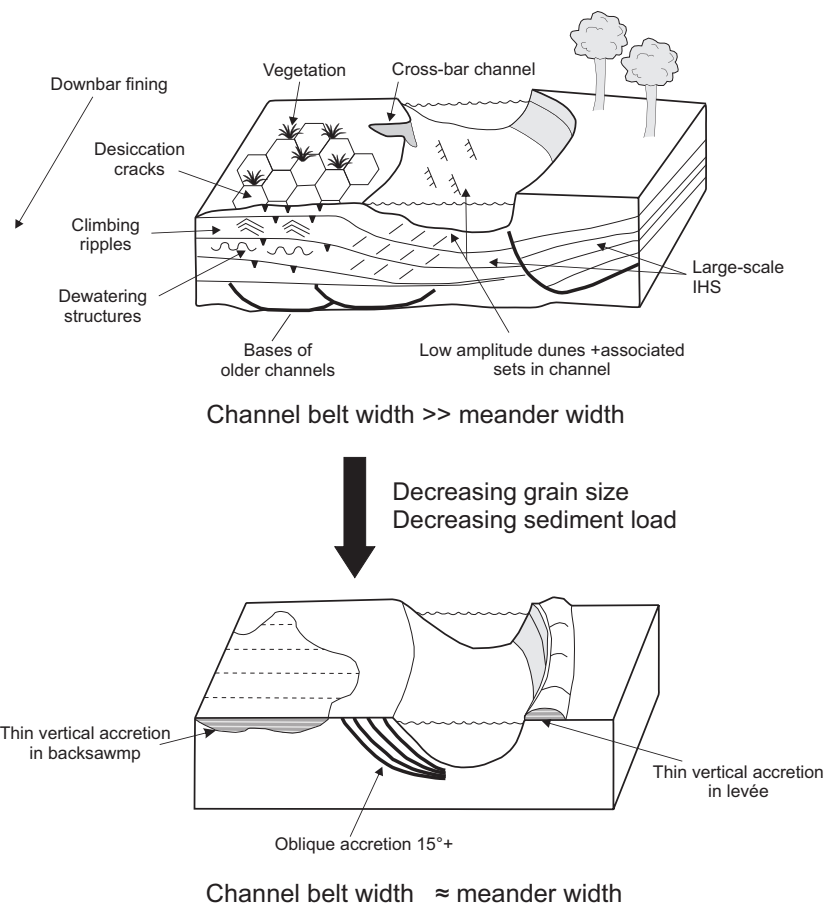


Fig. 20. Summary diagram of the alluvial architecture of fine-grained rivers. The top panel is based on the Río Bermejo – a highly active channel with a very high suspended sediment concentration. The lower panel is based on a synthesis of work presented in Gibling *et al.* (1998), Page *et al.* (2003) and Marren *et al.* (2006), and represents a case at the other end of the spectrum where channel migration rates and suspended sediment concentrations are much lower. A range of channel types exist between these two end members, such as those with a lower point-bar and upper oblique accretion deposits (Page *et al.*, 2003).

surfaces that are truncated and overlain by vertical accretion deposits; (ii) cross-sets associated with small bars and dunes; (iii) climbing ripples in the upper bar deposits; and (iv) cut and fill from smaller cross-bar channels. It is also evident that fine-grained alluvial deposits need not be simply indicative of quiescent rivers, and that great care should therefore be taken in interpretations of such environments when based on limited exposure or core.

More broadly, the data presented herein demonstrate that fine-grained rivers are undoubtedly much more diverse and complex than has perhaps hitherto been recognized. On the basis of the new data from the Río Bermejo and a synthesis of the literature, it is proposed that the end members of these fine-grained meandering rivers may be dominated by either lateral accretion or oblique accretion, depending on grain size and sediment load. Furthermore, the parametric echosounder (PES) technique utilized herein has the potential to be a transformative tool in fluvial sedimentology, providing the type of high-resolution data for fine-grained rivers that ground-penetrating radar has for coarse-grained rivers. There is clearly now a need for additional PES surveys from a broader range and size of fine-grained rivers to help to fully characterize their alluvial architecture.

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